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Discovery of an O VI Emitting Nebula around the Hot White Dwarf KPD 0005+5106

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ABSTRACT

A survey of diffuse interstellar sight lines observed with the *Far Ultraviolet Spectroscopic Explorer* has led to the serendipitous discovery of a high-ionization nebula around the hot white dwarf KPD 0005+5106. The nebula has an O VI λ1032 surface brightness of up to 25,000 photons s^{-1} cm^{-2} sr^{-1}, making it the brightest region of extended O VI emission in our survey. Photoionization models using the incident white dwarf continuum successfully reproduce the observed O VI intensity. The O VI emission arises in the highly ionized inner region of a planetary nebula around KPD 0005+5106. This newly discovered nebula may be one member of a class of high-ionization planetary nebulae that are difficult to detect in the optical, but which can be easily identified in the ultraviolet.

Subject headings: Circumstellar matter — Planetary nebulae: general — Stars: individual (KPD 0005+5106) — Ultraviolet: ISM — White dwarfs

1. INTRODUCTION

Planetary nebulae (PNe) come in a variety of shapes, irregular, bipolar, or spherical, and exhibit emission from forbidden lines such as [O III], [Ne III], and [Ne V] as well as from the Hα recombination line. In addition, numerous high-excitation PNe exhibit most of the other Balmer lines as well as He II, C III], and other forbidden lines such as [Ne IV], [Ar IV], [Mg V]. The typical radial extent is a few tenths of a parsec. Only a few PNe have radii exceeding 1.5 pc. Because of their small size and low surface brightness, PNe are notoriously difficult to discover (e.g., Kwitter et al. 1989; Werner et al. 1997; Rauch 1999).

We report the discovery of an O VI emitting nebula around KPD 0005+5106 with the *Far Ultraviolet Spectroscopic Explorer (FUSE)* that we identify as a high-ionization PN (HIPN) around this white dwarf (WD). This would make KPD 0005+5106 only the third WD (out of 162 WDs listed by Napiwotzki 1999) known to have a PN. Including KPD 0005+5106, only eight of the fifteen stars listed with $T_{\rm eff} \geq 120,000$ K (Napiwotzki 1999) have a known PN.

2. OBSERVATIONS

The *FUSE* instrument consists of four optical systems. Two employ LiF coatings and are sensitive to the wavelength range 990 – 1187 Å. The other two use SiC coatings and are sensitive to wavelengths between 905 and 1100 Å. Each spectrograph possesses three apertures that simultaneously observe different positions on the sky separated by a few arcminutes (for a complete description of *FUSE*, see Moos et al. 2000; Sahnow et al. 2000).

Because of the strong interstellar H_2 features in its spectrum, the WD KPD 0005+5106 was selected as a wavelength-calibration target and has been observed repeatedly throughout the mission. When the *FUSE* high- or medium-resolution aperture is centered on the star, the low-resolution (LWRS) aperture samples a $30'' \times 30''$ region 1.8 or 3.5 arcmin (respectively) away. Changes in the spacecraft roll angle from one observation to another place the LWRS aperture at different position angles around the star. Figure 1 shows the observed LWRS positions. In three additional background observations, the LWRS aperture was 2.2 arcmin from the star.

Table 1 lists the observational data for each pointing: observation ID, equatorial coordinates of the LWRS aperture, date of the observation, and the polar coordinates for the LWRS aperture relative to KPD 0005+5106. Angle φ is measured counterclockwise from the north celestial pole. A map key identifies the LWRS positions in Figure 1. All observations were performed in time-tag mode, in which the spectrograph records the position and arrival time of each photon.

3. DATA REDUCTION

The individual exposures of each pointing were aligned using the measured positions of the O I airglow lines between 1027 and 1042 Å. The data were screened for pulse heights in the range 2 – 25, shifted to a heliocentric wavelength scale, and combined, and the region around the O VI $\lambda\lambda$ 1032,1038 doublet was extracted. The spectra were binned by 16 pixels

to increase the signal-to-noise ratio. A more detailed description of the data reduction can be found in our O VI emission survey paper (Otte, Dixon, & Sankrit 2004, in preparation).

In most cases, we used night-only data to avoid possible contamination by an unidentified airglow feature near the O VI λ1032 line. For M1070208, M1070223, and M1070224, we combined day and night data to obtain a more reliable measurement of the faint O VI emission; contamination by the airglow feature could be excluded in these cases (by comparing the day-plus-night and night-only data).

Due to their nearly identical positions, the data of observations M1070211 and M1070214 were combined into one spectrum, as were the data of observations M1070212 and M1070215. Although the overlap of their positions is less than for the other two combined observations, we combined M1070209 and M1070221 to gain signal-to-noise at the expense of spatial resolution.

4. RESULTS

All spectra were fit using the IRAF[1] routine SPECFIT (Kriss 1994) with emission-line models consisting of a convolution of a Gaussian and a 106 km s^{-1} wide flat-top profile representing the LWRS aperture. The spectrum with the brightest O VI λ1032 feature (S4054403, map key 3) is shown in Figure 2.

The intensities derived from our fits to the O VI emission lines are listed in Table 2. Due to its low signal-to-noise ratio, possible blending with the C II* λ1037 line, and vicinity to the O I λ1039 airglow line, the O VI λ1038 emission line was difficult to fit in many cases. To date, the intensities of diffuse O VI λ1032 emission detected with *FUSE* range from 1700 to 11,000 LU, with an average value of 4700 ± 2400 LU (Otte, Dixon, & Sankrit 2004, in preparation)[2]. With a peak intensity of 25,000 LU, the high-ionization nebula around KPD 0005+5106 is the brightest region of extended O VI emission yet found.

[1]IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

[2]We note that O VI emission $10 - 100$ times brighter is detected in supernova remnant shocks. These, however, are well identified nebulae and not considered part of the diffuse interstellar medium.

5. DISCUSSION

With a surface temperature $T_{\rm eff} = 120,000$ K, KPD 0005+5106 is the hottest known DO (i.e. helium-rich) WD. The stellar spectrum has been observed at X-ray, ultraviolet, and optical wavelengths. Model fits yield stellar parameters of $\log(g) = 7$, $E(B-V) = 0.13$, and a distance of about 270 pc (Werner, Heber, & Fleming 1994; Werner et al. 1996). The star possesses a soft X-ray corona (O'Dwyer et al. 2003), and appears to undergo mass ejection (Werner et al. 1996; Sion et al. 1997).

In the $\log(g) - \log(T_{\rm eff})$ diagram, KPD 0005+5106 lies between the highest-gravity PG 1159 stars known to have PNe and the two DO WD PN candidates PG 0108+101 and PG 0109+111. The discovery of a PN around the DO WD PG 1034+001 (Hewett et al. 2003) extends the range of known PNe in the $\log(g) - \log(T_{\rm eff})$ plane along the evolutionary tracks toward lower temperatures and higher surface gravities ($\log(g) = 7.5, T_{\rm eff} = 100,000$ K; Werner, Dreizler, & Wolff 1995). KPD 0005+5106 lies well within this extended parameter space. However, previous searches for an optical PN around this WD have been unsuccessful (Werner et al. 1997).

Photoionized O VI is expected from PN with hot central stars ($T_{\rm eff} \geq 120,000$ K) and has been detected in a few such objects (Chu, Gruendl, & Guerrero 2004). We used the photoionization code CLOUDY to determine whether photoionization of a putative PN around KPD0005+5106 could explain the detected O VI emission. For the ionizing source, we used a synthetic spectrum of the star calculated with the program TLUSTY (Hubeny & Lanz 1995), using the observed stellar abundances and parameters (Werner et al. 1996). The stellar model was scaled to the flux observed with *FUSE*. Simple PN expansion models by Osterbrock (1989) yield densities of a few cm^{-3} at the distances of the LWRS aperture positions for a $\sim 10,000$ yr old PN. We assumed solar abundances and a particle density of unity (i.e., $n(\rm H) = 1$ cm^{-3}) in the absorbing cloud. With no other free parameters, our model reproduces the observed O VI flux to within a factor of a few. Based on this agreement between model predictions and observations, we conclude that the O VI nebula around KPD 0005+5106 is photoionized. It may be one of a new class of HIPNe that are faint in standard optical lines.

6. IMPLICATIONS

6.1. The KPD 0005+5106 System

Our photoionization model predicts a [Ne V] $\lambda 3426$ intensity seven times as bright as the O VI emission, whereas shock models yield [Ne V] intensities $10-100$ times fainter than the O VI emission. This discriminant has been used to argue that the nebula LMC 62 in the Large Magellanic Cloud is photoionized (Herald & Bianchi 2004). Assuming $E(B-V) = 0.13$, $R_{\rm V} = 3.2$, and extrapolating the extinction parameterization of Cardelli, Clayton, & Mathis (1989) to the Lyman limit, we find that the [Ne V] emission should be about 20 times brighter than the observed O VI $\lambda 1032$ emission around this WD. The photoionization model predicts that the [Ne V] emission arises in a more extended zone than the O VI emission. Though the geometry of the emitting gas is unknown, [Ne V] imaging would allow us to confirm the existence of HIPNe around this and other hot WDs.

Another prediction of a radiation-bounded HIPN is the presence of a low surface brightness Hα and [O III] $\lambda 5007$ nebula with a large angular diameter as has been observed around PG 1034+001 (Hewett et al. 2003), because lower ionization states are only possible at larger distances from the hot star. The PN search around KPD 0005+5106 by Werner et al. (1997) likely had too small a field of view to detect such an extended PN.

6.2. PN Populations and Evolution

As the central star of a PN contracts and its temperature rises, its radiation field becomes harder. Meanwhile, the expansion of the nebula causes its density to fall. The combination of these effects raises the ionization parameter (the ratio of photon density to particle density) at the inner face of the nebula, and with it the ionization state of the gas. This scenario has two implications: first, that every PN with a central star massive enough to reach a temperature greater than $\sim 120,000$ K will eventually pass through a high-ionization phase; second, that every hot white dwarf should exhibit a HIPN.

Observations of HIPNe around hot WDs may reveal important information about WD precursors and their evolution. One unresolved problem, for example, is the existence of helium-rich, hydrogen-deficient WDs that account for about 20% of all known degenerate stars (Sion et al. 1997). With the precursors' abundances imprinted in the diffuse gas, HIPNe could give clues to the evolutionary process that results in this bizarre type of WDs.

The photoionization model with unit hydrogen density and solar abundances, [O/H]$=7.4\times10^{-4}$, predicts that the thickness of the O VI emitting zone is approximately 5×10^{18} cm.

In this region, the fractional abundance O^{5+}/O is about 0.11, which translates to a number density $N_{O^{5+}} \sim 8 \times 10^{-5}$ cm^{-3}. The O VI column density is thus about 4×10^{14} cm^{-2}. Depending on the distribution of hot WDs in the Galactic disk, HIPNe could contribute a significant fraction to the total O VI column density in the plane.

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Table 1. OBSERVATIONS

Observation ID	RA[a]	DEC[a]	Observation Date	φ (deg)	Distance (pc)	Map Key
M1070205	0 07 56.0	51 22 50	2001-09-29	262.52	0.27	12
M1070206	0 08 06.7	51 23 03	2001-09-29	262.35	0.14	10
M1070208	0 07 59.2	51 25 00	2002-08-23	299.57	0.27	15
M1070209	0 08 08.3	51 24 10	2002-08-23	299.35	0.14	13
M1070211	0 08 00.1	51 21 11	2002-10-21	232.79	0.27	9
M1070212	0 08 08.9	51 22 11	2002-10-22	232.20	0.14	7
M1070214	0 08 00.6	51 21 05	2002-10-23	230.64	0.27	8
M1070215	0 08 09.1	51 22 08	2002-10-23	230.44	0.14	6
M1070217	0 08 22.3	51 19 53	2002-12-17	167.76	0.27	1
M1070221	0 08 09.7	51 24 28	2003-08-07	311.16	0.14	14
M1070223	0 08 17.2	51 19 49	2003-12-03	180.87	0.27	4
M1070224	0 08 17.7	51 21 29	2003-12-03	180.67	0.14	2
S4053801	0 08 04.7	51 22 44	2001-10-23	255.41	0.17	11
S4053803	0 08 11.6	51 21 20	2003-12-02	206.43	0.17	5
S4054403	0 08 15.9	51 21 07	2002-12-22	187.78	0.17	3

[a]Coordinates are J2000.0 and refer to the center of the *FUSE* low-resolution aperture. Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

Table 2. O VI INTENSITIES

Map Key	t (sec)	I_{1032} (10^3 LU)[a]	I_{1038} (10^3 LU)[a]
1	3157	< 8[b]	< 8[b]
2	2773	25 ± 7	12 ± 4
3	3250	25 ± 4	11 ± 3
4	2752	18 ± 8	12 ± 9
5	1890	18 ± 5	15 ± 4
6/7	5789	19 ± 3	17 ± 3
8/9	3953	18 ± 4	8 ± 3
10	2483	17 ± 4	9 ± 3
11	11010	16.2 ± 2.4	11.1 ± 2.8
12	2691	20 ± 4	16 ± 6
13/14	6279	12 ± 4	5.4 ± 2.0
15	4214	8 ± 3	8.0 ± 2.4

[a] 1 LU = 1 photon s^{-1} cm^{-2} sr^{-1}; for O VI λ1032, 1 LU = 4.5×10^{-22} erg s^{-1} cm^{-2} $arcs^{-2}$.

[b] Value is a 2 σ upper limit.

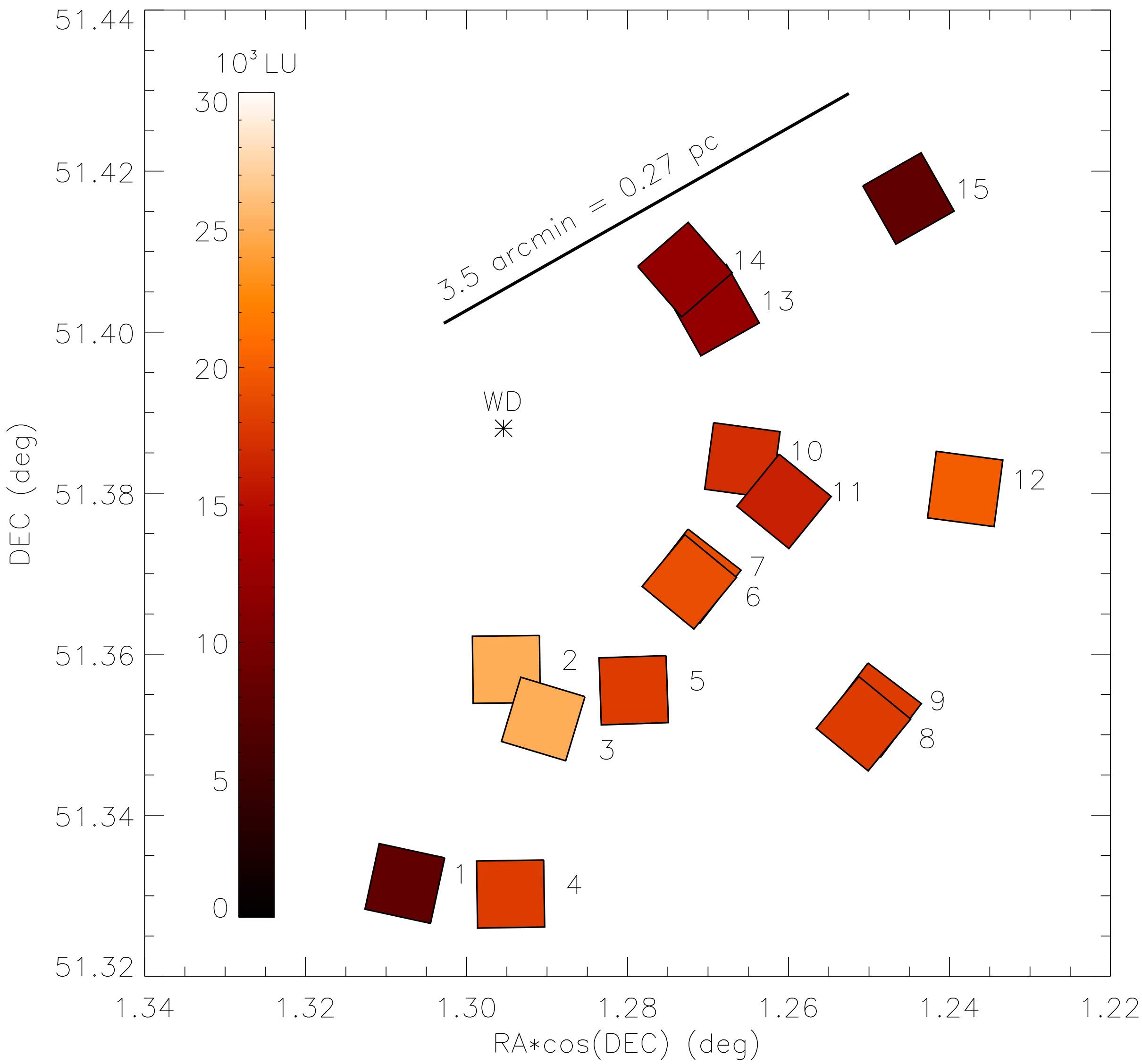

Fig. 1.— Observations of diffuse O VI emission around the hot WD KPD0005+5106. Colors represent the O VI λ1032 intensity in units of 10^3 LU (LU $\equiv$ photons s^{-1} cm^{-2} sr^{-1}) recorded through the *FUSE* LWRS aperture. The angular distance from the star to the center of each aperture in the outer ring is 3.5 arcmin; at a distance of 270 pc, this corresponds to about 0.27 pc. Numbers refer to the map key listed in Tables 1 and 2.

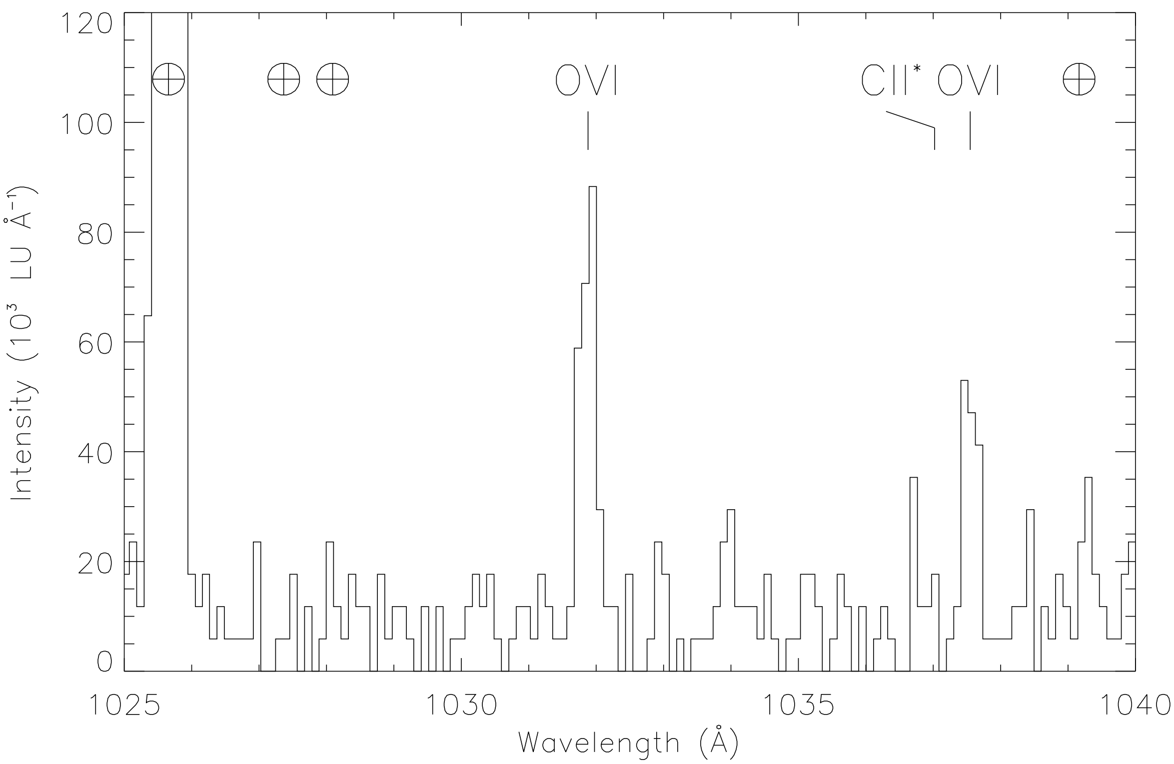

Fig. 2.— Spectrum of sight line S4054403 (map key 3). This sight line exhibits the strongest O VI emission measured in the nebula around KPD 0005+5106. The O VI doublet and the C II* λ1037 emission line are labeled. The positions of airglow lines are marked with the Earth symbol.